Precision Formation Flying (PFF)

Earth Science Technology Conference

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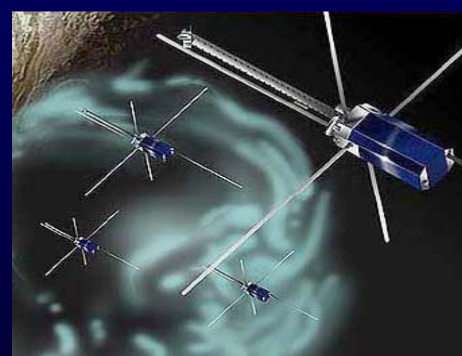
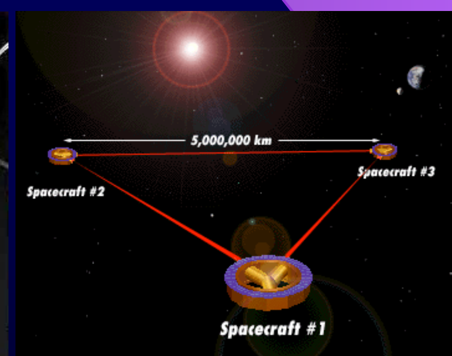
Agenda

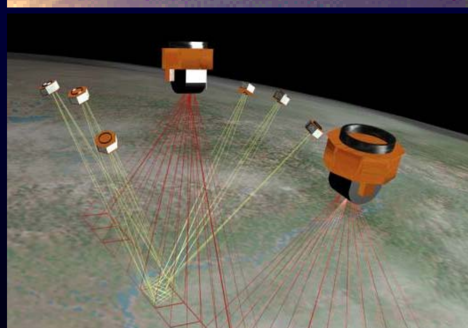
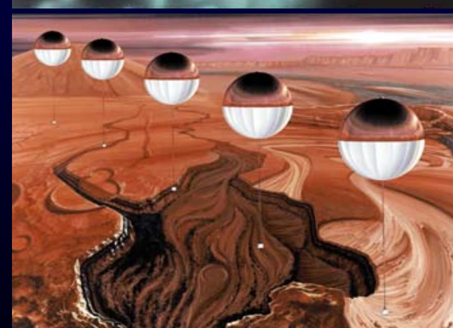
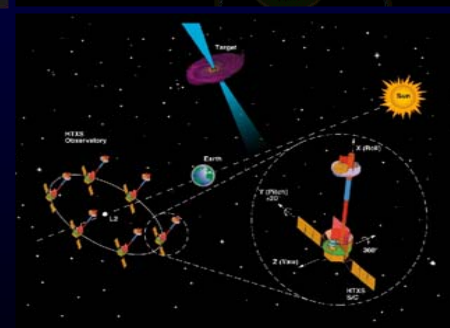
- **Overview**
  - Formation Flight/Constellations/Fleets
- **Formation Flying Missions**
  - US
  - Non US
- **Formation Flying Technologies**
  - Components
  - Flight Experiments
  - Ground Testbeds
- **Summary**

Formation Flying Spacecraft

A Set of Spatially Distributed Spacecraft Flying in Formation with the Capability of Interacting and Collaborating with One-another, and Work as a Single Collective Unit, Exhibiting a System-wide Capability to Accomplish Shared Objectives

spacecraft states are dynamically coupled through control

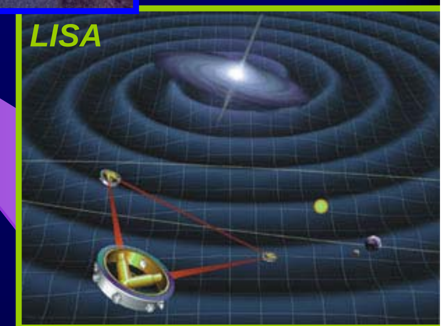




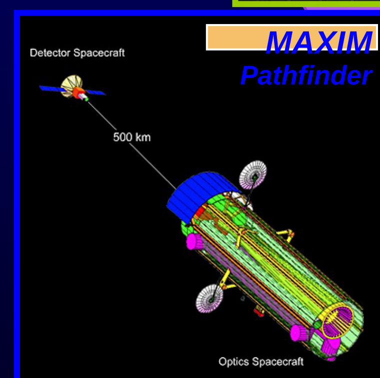
What is Precision Formation Flight? (PFF)

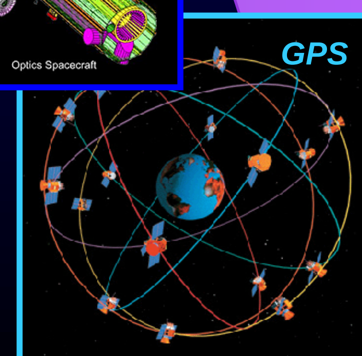
- **Based on inter-connections between spacecr divide multiple-spacecraft missions into:**

Formation Flying Technology

- **Precision Formations**
  - Inter-spacecraft communication, precise sensing, and autonomous control = Inter-spacecraft coupling
  - Examples: Stellar Imager, TPF-I, MAXIM
- **Knowledge Formations**
  - Inter-spacecraft sensing
  - No inter-spacecraft control
  - Examples: LISA, GRACE
- **Collaborative Systems**
  - Inter-spacecraft sensing and control for limited durations
  - Not maintaining long duration formations
  - Examples: Automated On-Orbit Assembly, Autonomous Rendezvous
- **Constellations**
  - No inter-spacecraft coupling
  - Examples: GPS, Cluster
- **Fleets**
  - Combination







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Future Formation Flying Mission Concepts

Partial List of Science Investigations Enabled by Distributed Spacecraft Systems:

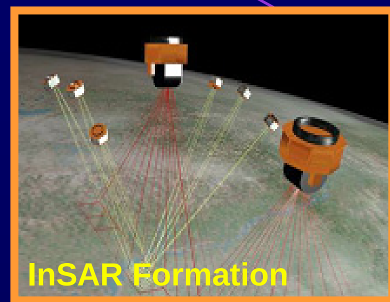
- Planet finding and imaging
- Resolving the cosmic structure
- 3-D mapping for planetary explorers
- Time-varying gravity field measurements
- Gravity wave detection
- In situ magnetosphere and radiation
- Electrodynamics environment of near-Earth space
- Earth radioactive forcing
- Soil moisture and ocean salinity
- Atmospheric chemistry
- Global precipitation
- Coordinated observing for land imaging
- Vegetation recovery
- Space weather

PFF Motivation

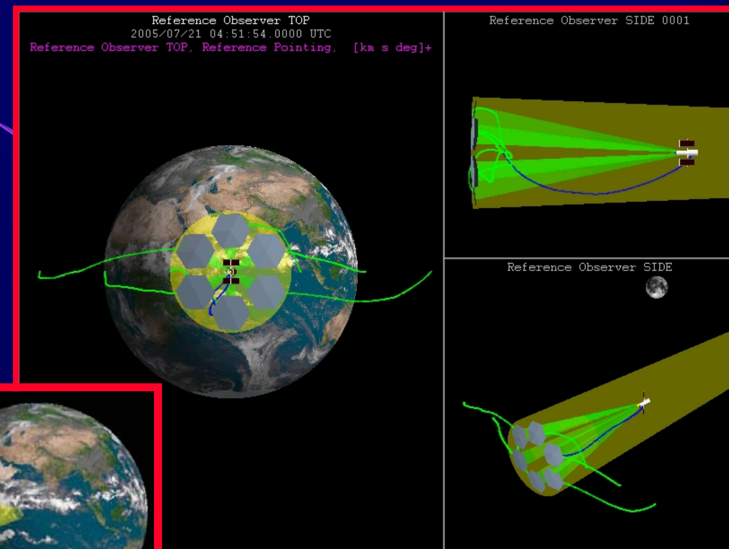
- **The angular resolution of a telescope is inversely proportional to its diameter**
  - The bigger the telescope the smaller/farther things you can see
- **Two small objects (as viewed from the Earth) of interest to scientists are**
  - Extra-solar, Earth-like Planets
  - Black holes
- **These objects necessitate telescopes with diameters ranging from tens to hundreds of meters**
  - The to-be-launched infrared James Webb Space Telescope will have a diameter of 6 meters
  - Wavelength ranges for these missions (infrared to X-ray) require precise surfaces
    - No inflatables yet
- **One solution is to *synthesize an aperture***

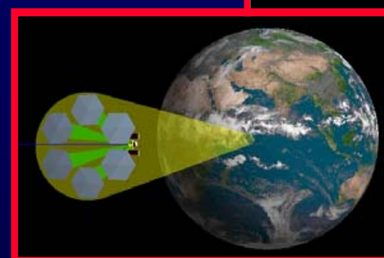
PFF Applications

- **Aperture Synthesis**
  - Exo-planet detection and characterization
  - Astrophysics
  - Surveillance
  - Communications
  - Synthetic Aperture Radar (SAR)
    - Interferometric SAR (InSAR)
- **Automated Rendezvous and Proximity/Docking Operations**
  - Lunar/Martian Sample Return
  - On-orbit Manufacturing
  - On-orbit Assembly
  - On-orbit Servicing
  - Reconnaissance of Space Assets

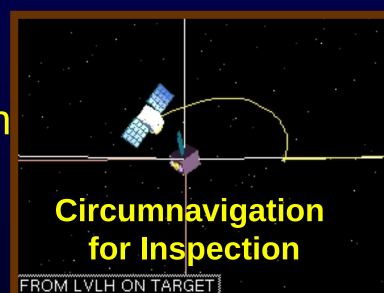


InSAR Formation

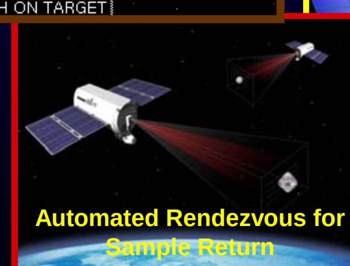




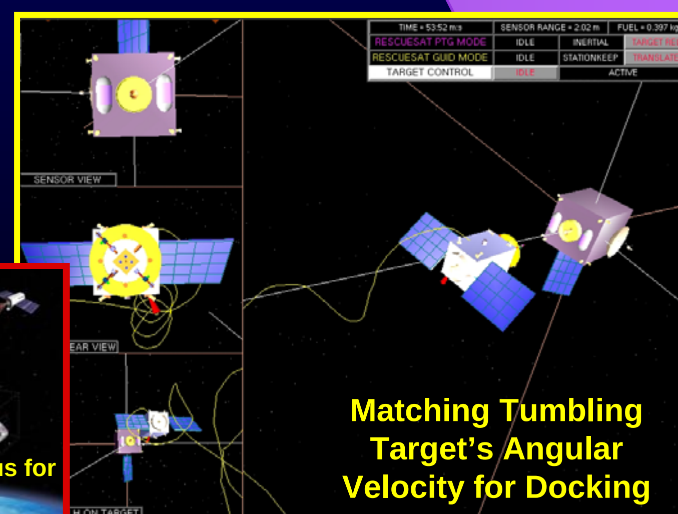
Sparse Aperture Synthesis for GEO Optical Surveillance



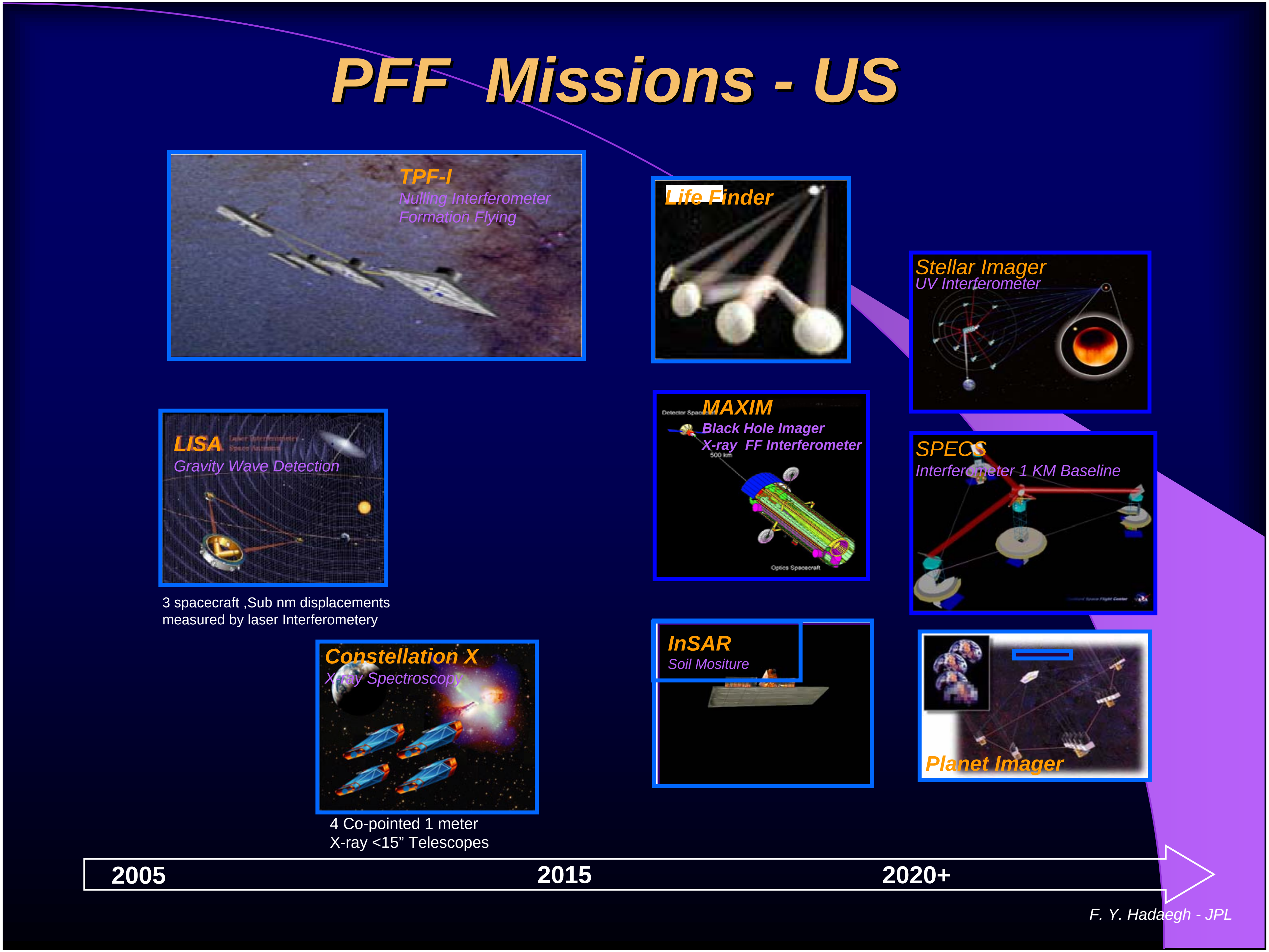
Circumnavigation for Inspection



Automated Rendezvous for Sample Return



Matching Tumbling Target's Angular Velocity for Docking


PFF Missions - US
TPF-I
Nulling Interferometer
Formation Flying
Life Finder
Stellar Imager
UV Interferometer
LISA
Gravity Wave Detection
3 spacecraft ,Sub nm displacements
measured by laser Interferometery
MAXIM
Black Hole Imager
X-ray FF Interferometer
500 km
Optics Spacecraft
SPECS
Interferometer 1 KM Baseline
Constellation X
X-ray Spectroscopy
4 Co-pointed 1 meter
X-ray <15" Telescopes
InSAR
Soil Mositure
Planet Imager
2005
2015
2020+
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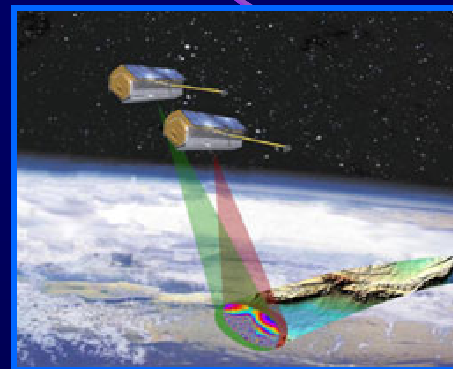
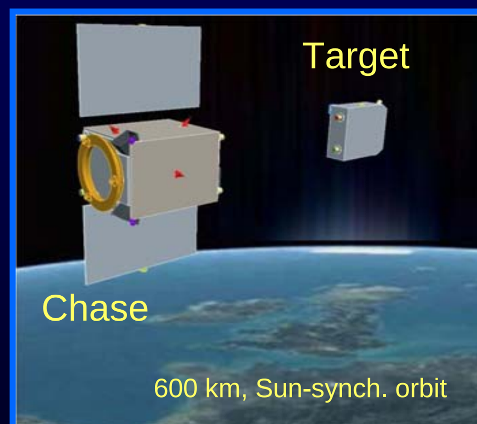
FF Missions (Non-US)

French (CNES) ESSAIM FF Demonstrator Mission
Dec. 2004

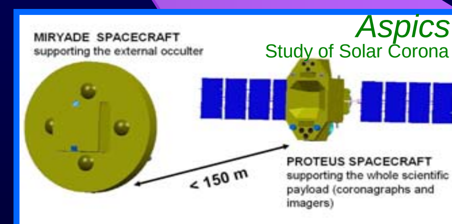
German (DLR) TanDEM-X Mission

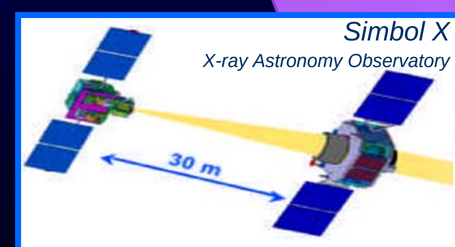


Japanese (NASDA) ETS-VII Mission
Nov. 1997



Swedish Prisma Mission - 2008





1990 2000 2010 2020+

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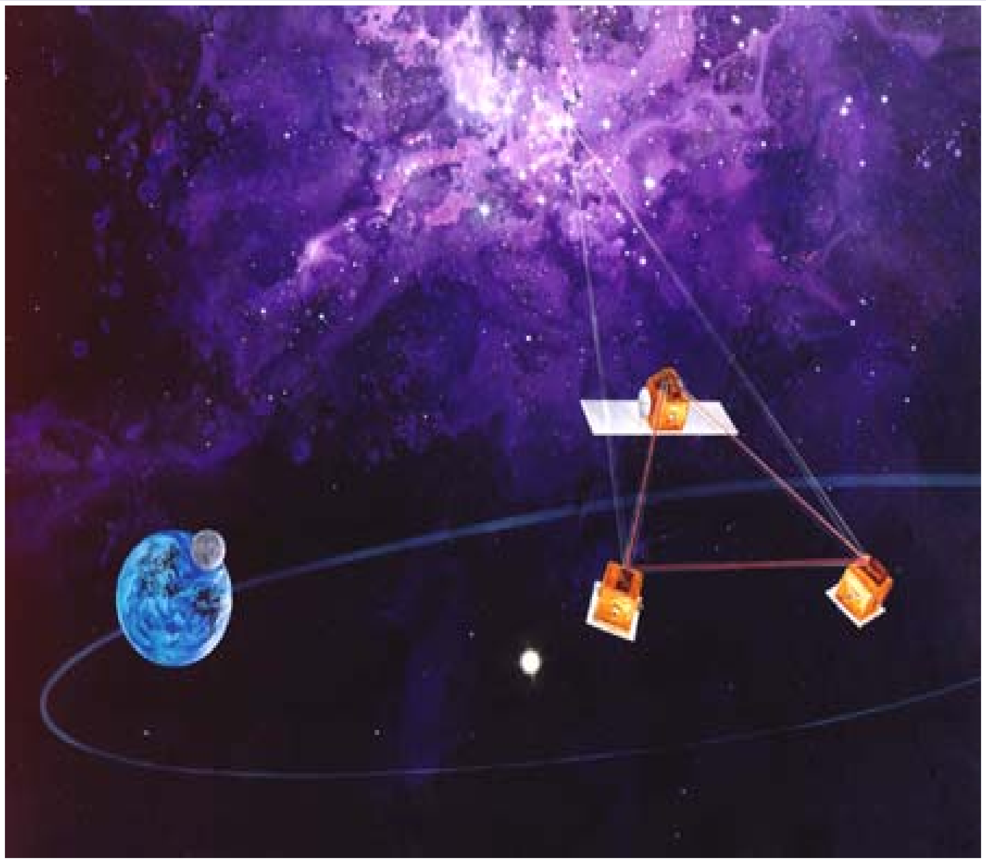
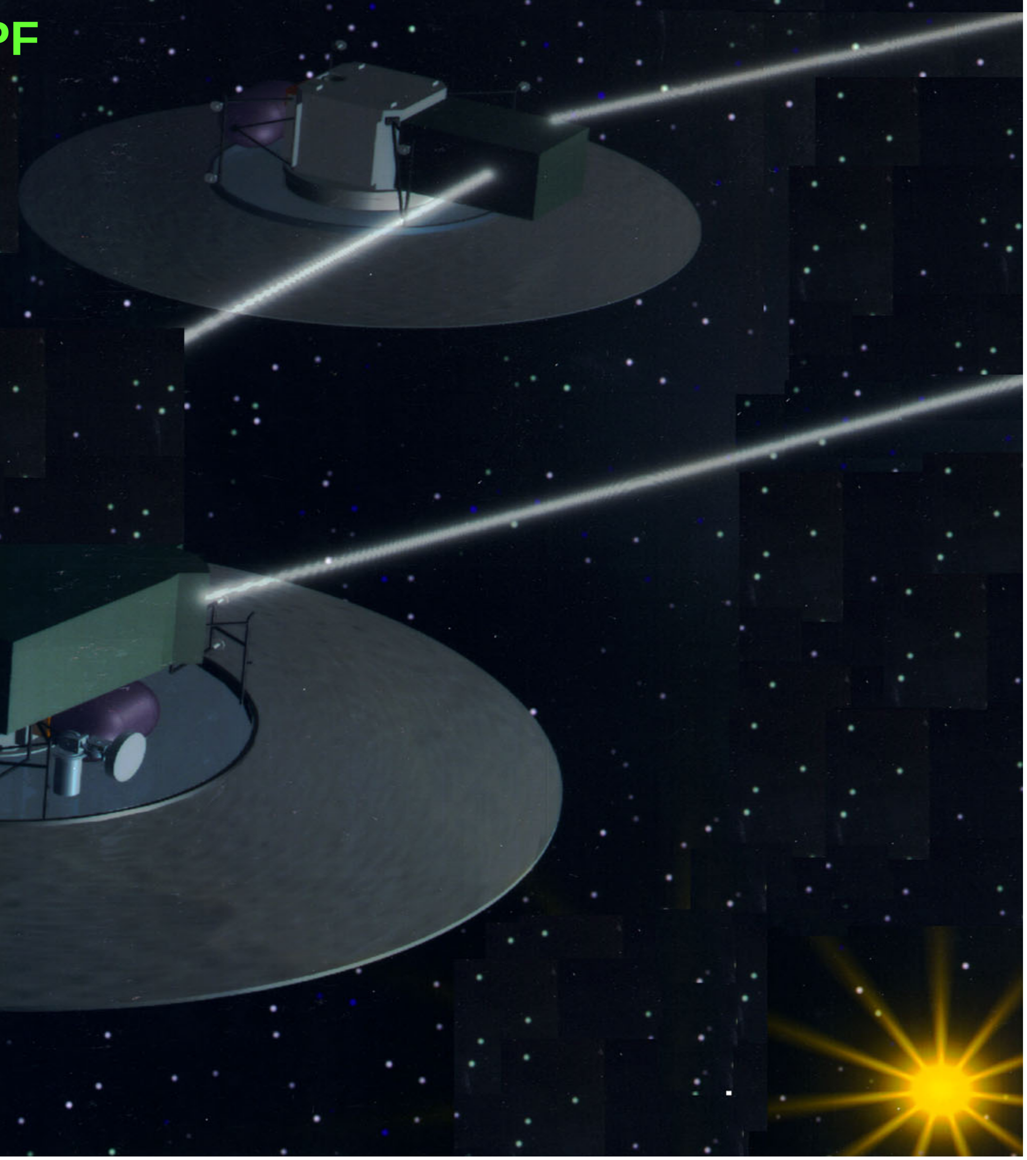
ST-3



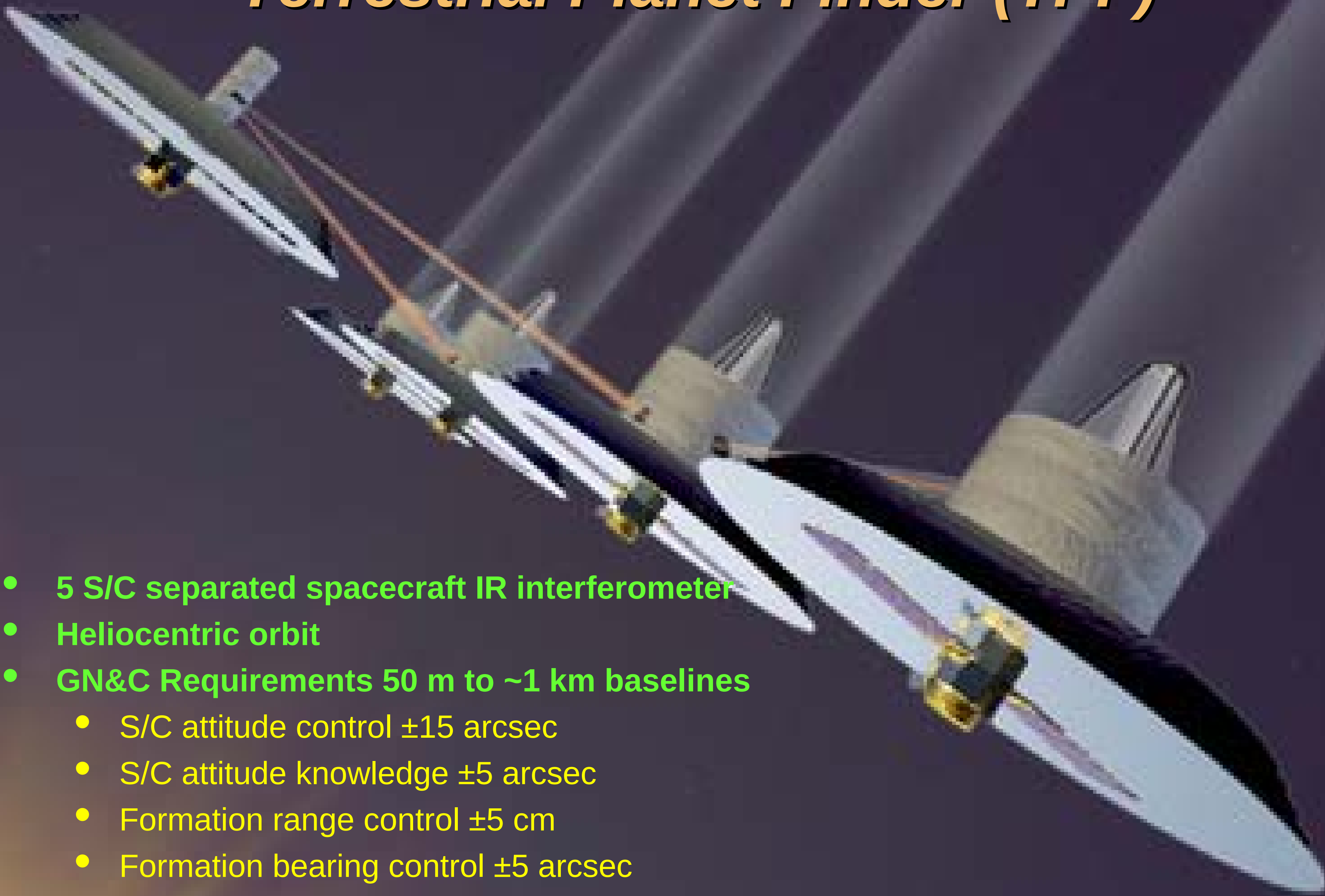
- **Precision Formation of Multiple Spacecraft Form a Single Virtual Science Instrument**
- **Increased Performance, Accuracy and Reliability**
  - Interferometric Imaging Without Large Truss
  - Distributed Computing via Interspacecraft Communication
  - No Single Point Failures
  - Autonomous Formation Keeping, Alignment and Reconfiguration

Starlight

- **Two (2) S/C mission**
- **Technology demonstration for TPF**
  - Formation flying
  - Separated S/C optical interferometry
  - Delta II 7325
- **Heliocentric orbit**
- **6 month mission**
- **GN&C Requirements**
  - 50 to 1010 m baselines
  - S/C attitude control ±1 arcmin
  - S/C attitude knowledge ±10 arcsec
  - S/C translational velocity control ±0.1 mm/sec
  - Formation range control ±3 cm
  - Formation bearing control
    - Acquisition ±0.7 arcmin
    - Observation ±6.7 arcsec

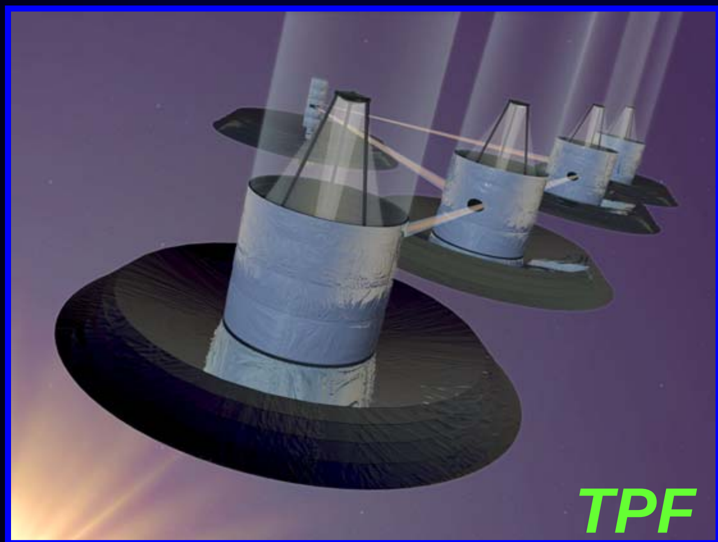


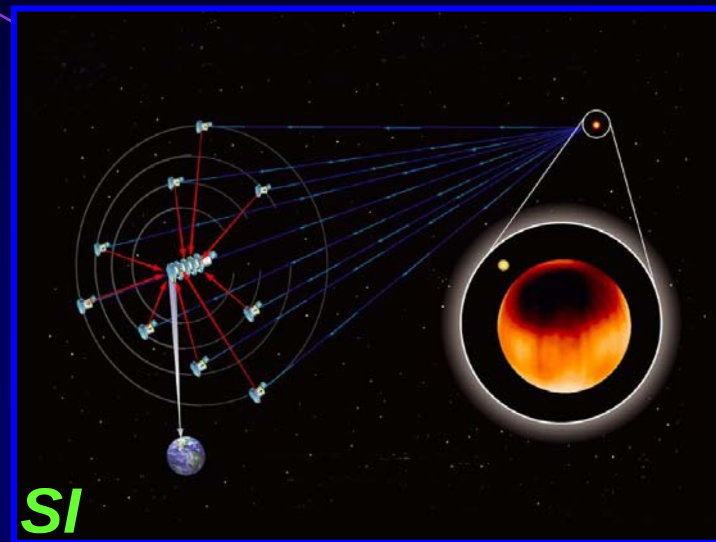
Terrestrial Planet Finder (TPF)

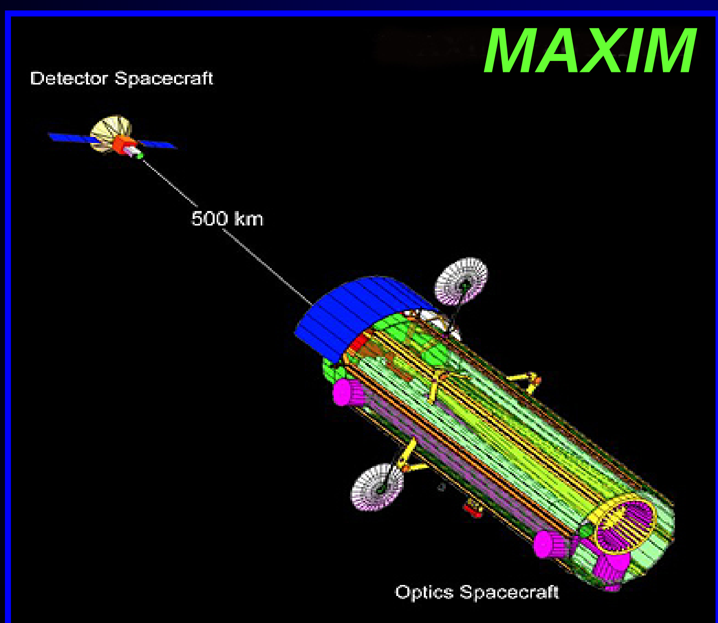


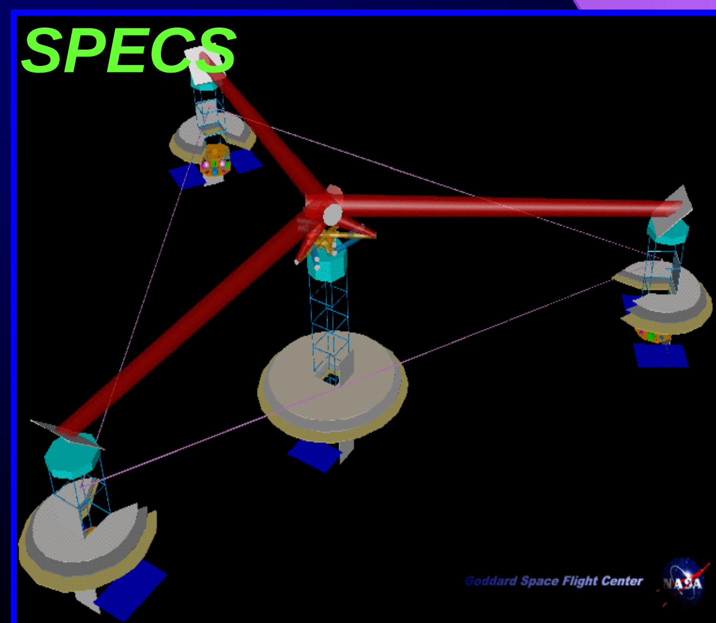
- **5 S/C separated spacecraft IR interferometer**
- **Heliocentric orbit**
- **GN&C Requirements 50 m to ~1 km baselines**
  - S/C attitude control ±15 arcsec
  - S/C attitude knowledge ±5 arcsec
  - Formation range control ±5 cm
  - Formation bearing control ±5 arcsec

Other PFF Missions









Technology Challenges

- **Formation control**
  - Hi precision sensors
  - Synchronous fleet reconfiguration/reorientation
  - Decentralized distributed control and estimation
  - Relative/absolute position and attitude control for precision interferometry
- **Extremely high precision/low noise thrusters, wheels, etc.**
- **Communication, cross-links, downlinks**
- **High speed distributed computing, data management & autonomy**
  - Collaborative behavior
  - Autonomous fault detection/recovery
  - Coordinated instruments and science planning/processing
  - Efficient numerical integrators which handle large scale variations in states (relative position and attitude)
- **High fidelity modeling and distributed real-time simulation**
- **HW Testbeds**
  - Ground testing of 6dof

Formation Actuation Technologies

Formation Flying Needs

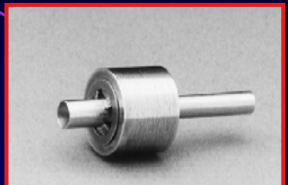
Coarse actuation for gross retargeting and formation reconfiguration, and
Precision actuation for stable and accurate pointing for science observations

- Reaction wheels can do both coarse & fine stage actuation, however:
  - Wide-band harmonic disturbances compromise on-board science
  - Controls only attitude degrees of freedom
- Coarse actuation technologies are relatively well developed, however:
  - Contamination of optical surfaces on science missions
  - Relatively low specific impulse (Isp)

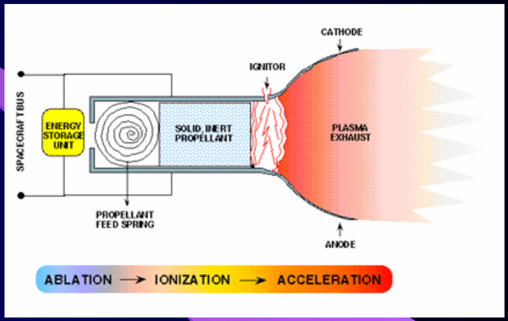
More development needed in non-contaminating Precision Actuation Technologies

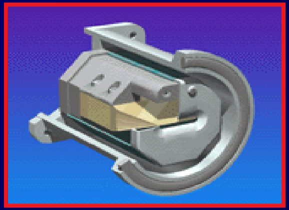
Spacecraft Actuation Technologies

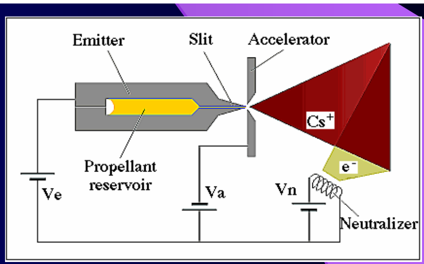
- **Cold gas (N_2) thrusters**
  - As small as 4.5 mN, <u>non-contaminating</u>
  - ST3 requires >50 mN due to solar press. and torques
  - Low I_{sp} (60 sec)
- **Pulse Plasma Thrusters (PPT)**
  - 700 µN per pulse, up to 6 Hz
  - Intermediate I_{sp} (typ. 500 - 1,500 sec)
  - High power
  - Contamination concerns
- **Field Electric Emission Propulsion (FEEP)**
  - 1 µN to 2 mN thrust
  - Very high I_{sp} (6000- 9000 sec)
  - High power (approx. 60W/mN)
  - Contamination concerns
- **Colloidal thrusters**
  - 1 µN to 100 µN thrust (ST7 Technology)
  - Historical tests performed at thrusts up to 1.3 mN
  - Intermediate Isp (500 - 1000 sec)
  - Low power (about 10W/mN)
  - Contamination and propellant irradiation concerns
- **Miniature Ion Thrusters**
  - 0.5 - 3 mN for 3-cm dia. engine
  - Scalable to larger thrusts for larger size thrusters
  - 3000 sec Isp
  - Approx. 30W/mN specific power
  - Xenon gas propellant: benign, <u>non-contaminating</u>, central tank feeding multiple thruster clusters

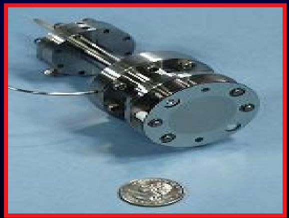


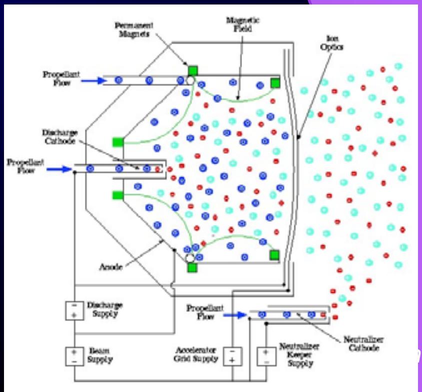
N_2 Cold Gas Thruster







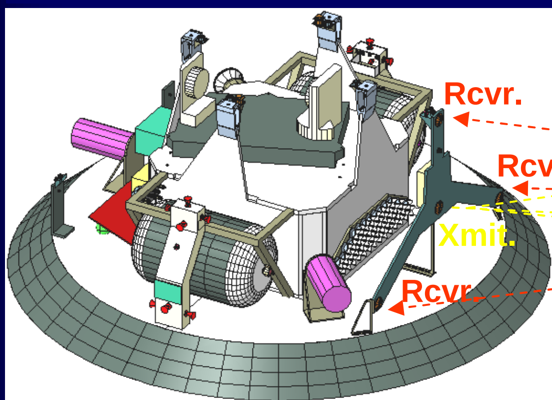




Spacecraft Actuation Technologies
- Comparison-

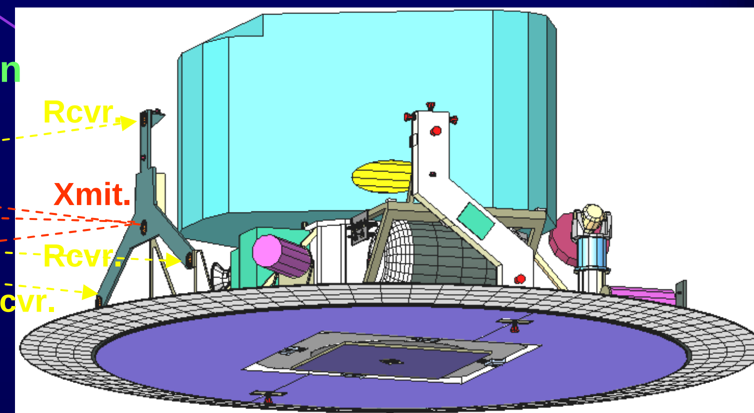
Thruster Type	Cold Gas	PPT	FEEP (Indium)	FEEP (Cesium)	Colloid	Miniature Ion
Thrust (mN)	4.5 - 4,500	0.002 - 0.7	0.001 - 0.5	0.001 - 1.4	0.001 - 0.1	0.5 - 3
Isp (sec)	60 (N_2)	500 - 1500	6,000 - 9,000	6,000 -9,000	500 - 1,500	3000 (typ.)
Ibit (Ns)	10^{-4}	10^{-4} - 10^{-6}	10^{-8} (est.)	10^{-8} (est.)	10^{-8} (est.)	TBD
Specific Power (W/mN)	N/A	70 - 100	60	60	10	30
Propellant	Typ. N_2	Teflon	Indium	Cesium	Glycerol, Ionic Liquids, Formamide	Typ. Xenon
Contamination Concerns	No	Yes	Yes	Yes	Yes	No
Comments	Central Tank Large required propellant volume	Modular Fuel Bar, Pulsed Operation Only	Modular Tank Design, Capillary Feed	Modular Tank Design, Capillary Feed	Modular Tank Design, Capillary Feed	Central Tank scalable to significantly higher thrusts for larger engines supercritical (compact) propellant storage

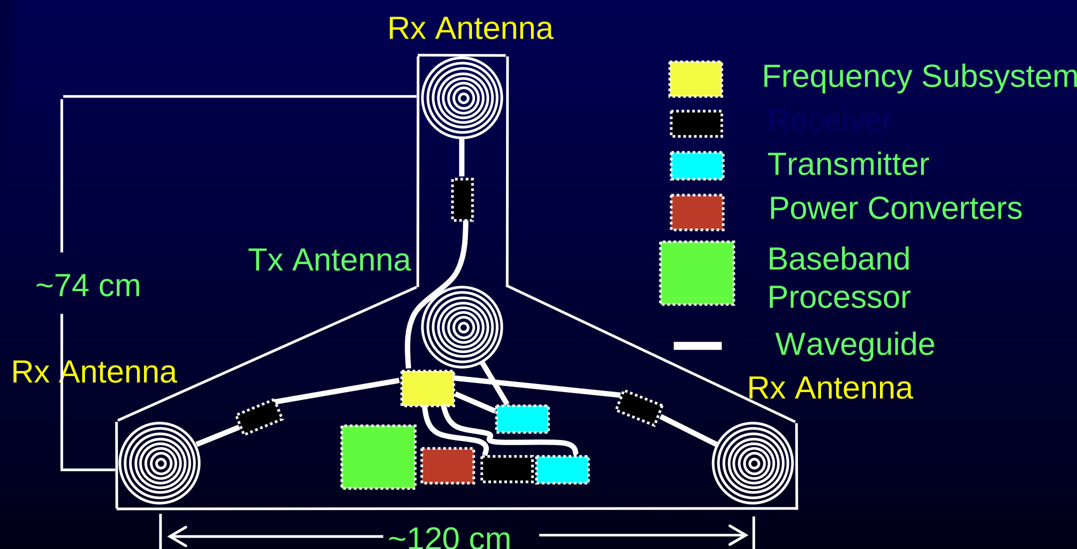
Formation Sensing Technologies

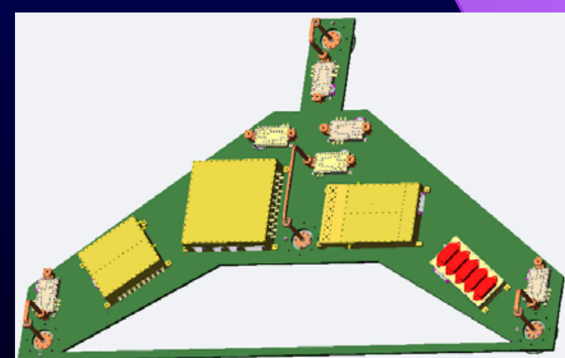


Operating Range = 30-1000 m
Range accuracy = 2 cm
Bearing accuracy = 1 arc-min
FOV (half-cone) = 70 deg

Comm. Channel = 1 kbit/s
RF Freq. = 30 Ghz







Electronics mounted on back of mounting plate

Autonomous Formation Flying (AFF) Sensor

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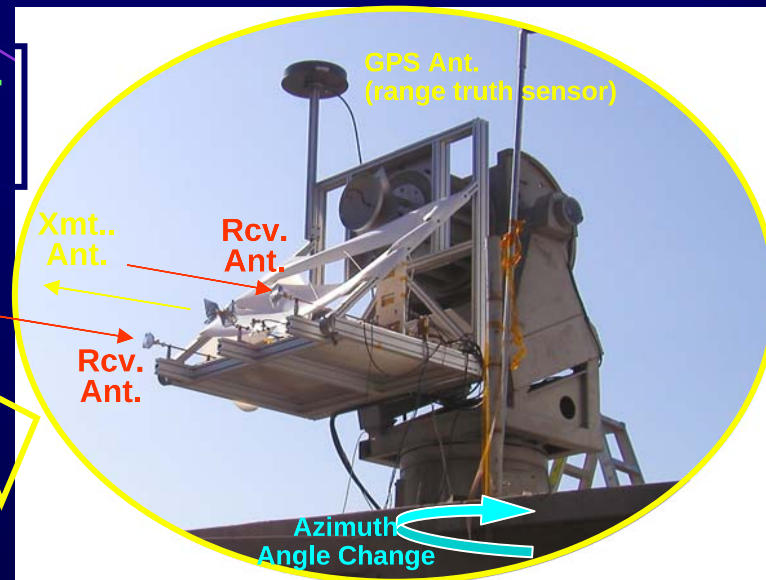
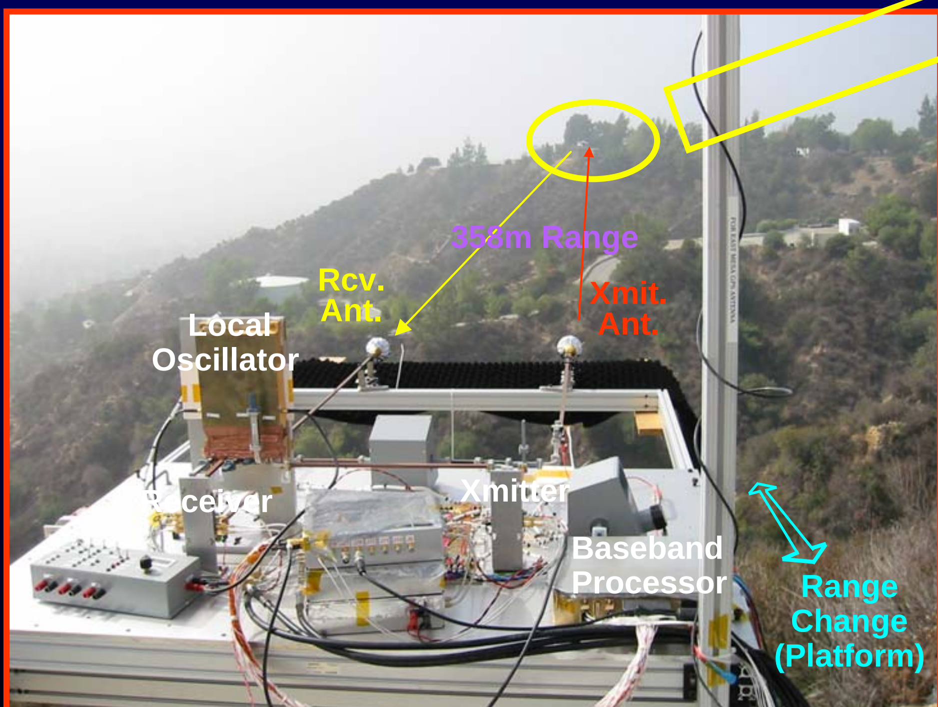
Formation Sensing Technologies - cont'd

Autonomous Formation Flying (AFF) Sensor Field-Test Setup



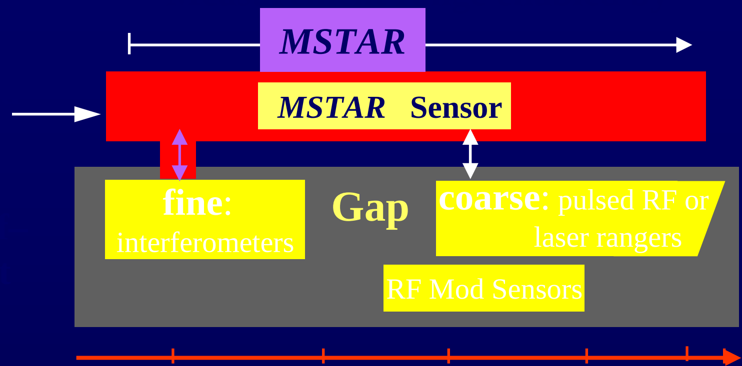


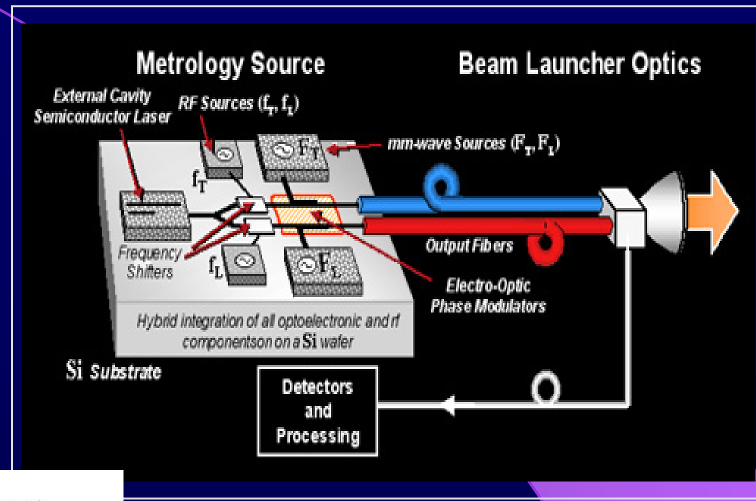
Demonstrated Performance:

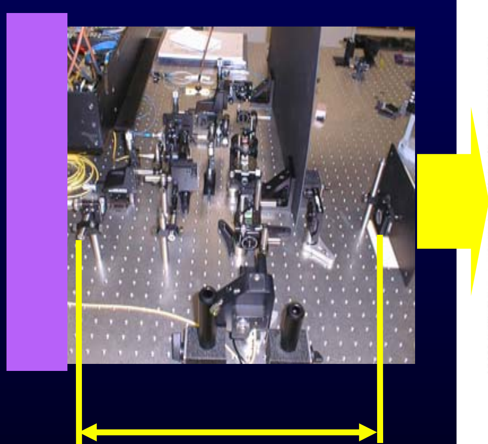
Range = 2cm

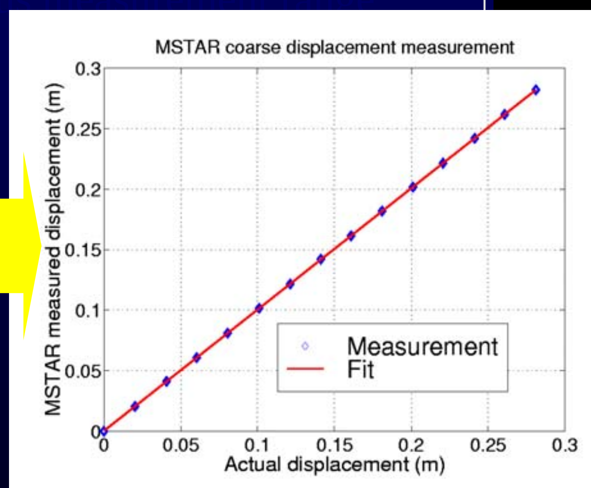
Bearing = 1 arcmin

Formation Sensing Technologies - cont'd









Nanometer precision, ultra-high dynamic range absolute range sensor.

Breadboard demonstrated in FY01

Modulation Sideband Technology for Absolute Ranging (MSTAR) Sensor

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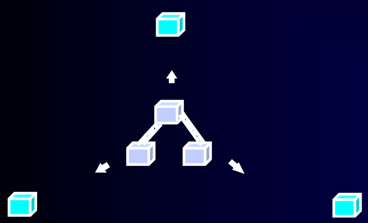
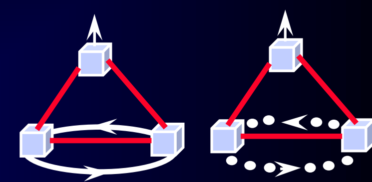
Formation Guidance & Control

Unique Capability



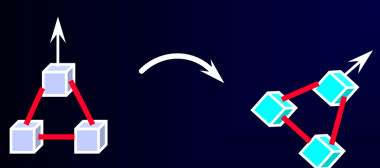
Formation Initialization

- Precision alignment (mm-cm, arcsec- arcmin),
- Synchronized motions,
- Autonomous reconfigurations of spacecraft

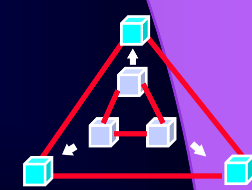


Formation Observation Slew

- formation acquisition,initialization & maintenance, station keeping
- formation maneuver planning and execution
- fault detection and recovery
- Scalable FF control architectures
- Autonomous guidance and control laws
- Formation estimation algorithms
- Testbed Demonstration of precision translation and synchronized rotations
- Precision formation controls optimized for time and/or fuel
- Data fusion of high number of formation sensors across many spacecraft
- Algorithms for optimal u-v plane mapping of science target
- Optimal Path planning
- Collision avoidance



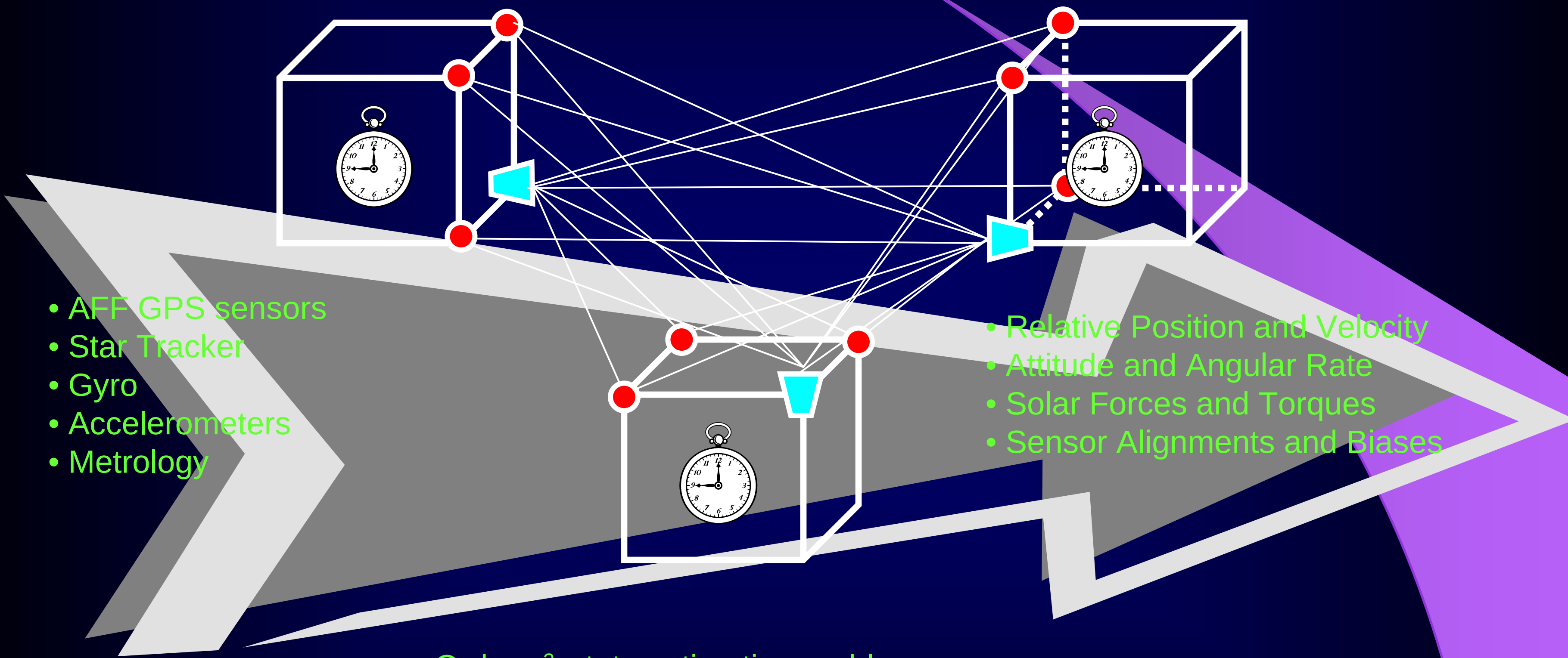
Formation Retargeting Slew



Formation Resizing

Formation Estimation

Unique Capability



- AFF GPS sensors
- Star Tracker
- Gyro
- Accelerometers
- Metrology

- Relative Position and Velocity
- Attitude and Angular Rate
- Solar Forces and Torques
- Sensor Alignments and Biases

- Order n^2 state estimation problem
- Centralized/decentralized
- Asynchronized data type
- Integrated position/attitude estimation
- Relative state (position or attitude) estimates are highly coupled

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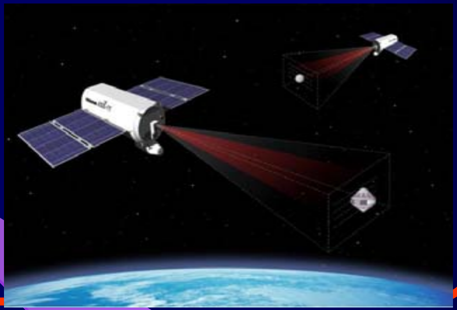
Formation Flying – Flight Tech Demo

ST6/XSS11 (ARX - Autonomous Rendezvous Experiment)

- NASA/AFRL
- Launch: 2005
- Operating range: 5000m-10m
- Mass: 110 kg

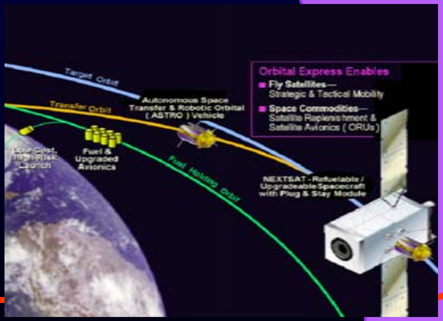


DART (Demonstration of Autonomous Rendezvous Technologies)

- NASA Space Launch Initiative
- Launch: 2005
- Mass: 350 kg
- Pegasus launch, ~15meter proximity operation, onboard Video Guidance Sensor (VGS)

Orbital Express

- NASA/DARPA
- Launch: 2006
- Mass: 300-500 kg
- Autonomous approach, docking, fuel transfer, repairs



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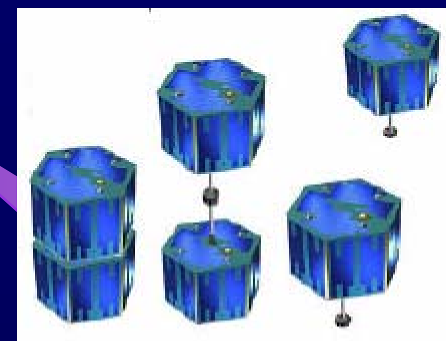
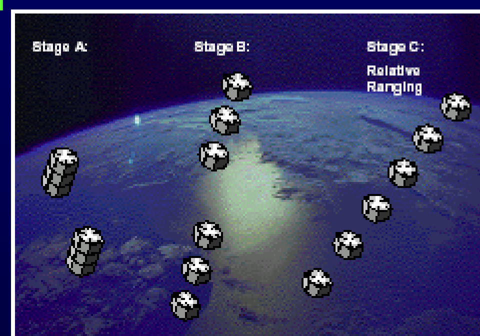
Formation Flying – Flight Testbeds

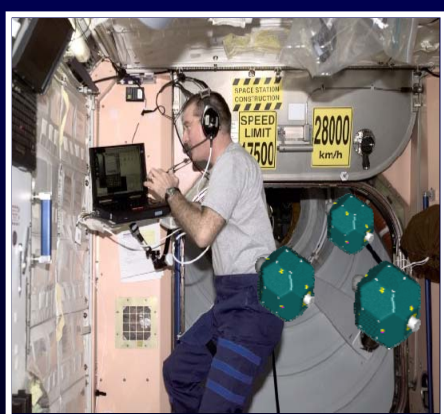
Three Corner Satellite Constellation (Stacked configuration)
Arizona State, Univ. of Colo., Boulder, New Mexico State Univ.



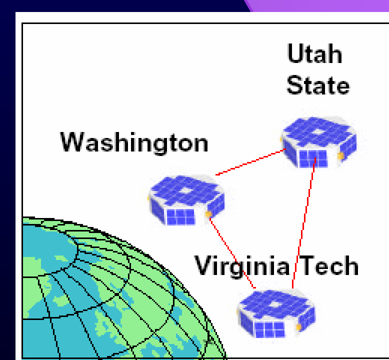
Emerald Spacecrafts
Stanford Univ., Santa Clara Univ.



ORION
GSFC/Stanford Univ.

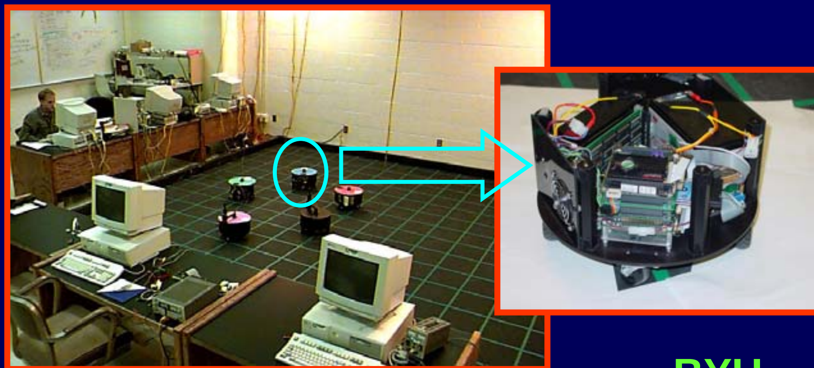


SPHERES
MIT



Ionospheric Formation
Utah State, Univ. of Washington, Virginia Polytechnic Institute & State Univ.

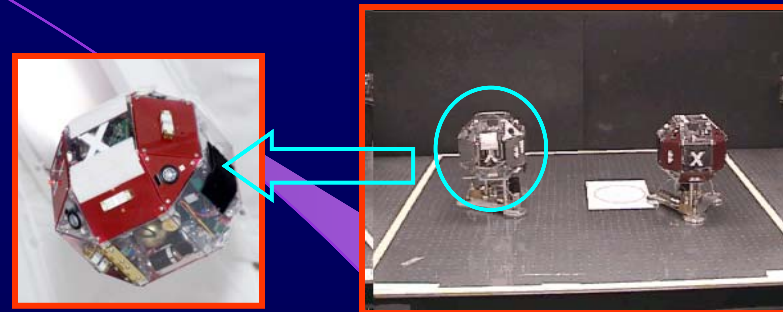
Formation Flying - Ground Testbeds



Multi-Agent Intelligent Coordinated Control

BYU

MIT



Synchronized Position Hold Engage Reorient Experimental Satellites - SPHERES

Realistic Dynamics with Air & Magnetic Levitation

FORMATION ACQUISITION & ATTITUDE ALIGNMENT TESTBED
(1998)

SYNCHRONIZED ROTATION TESTBED (2000)

FORMATION OPTICAL ALIGNMENT TESTBED
(2002)

JPL/UCLA

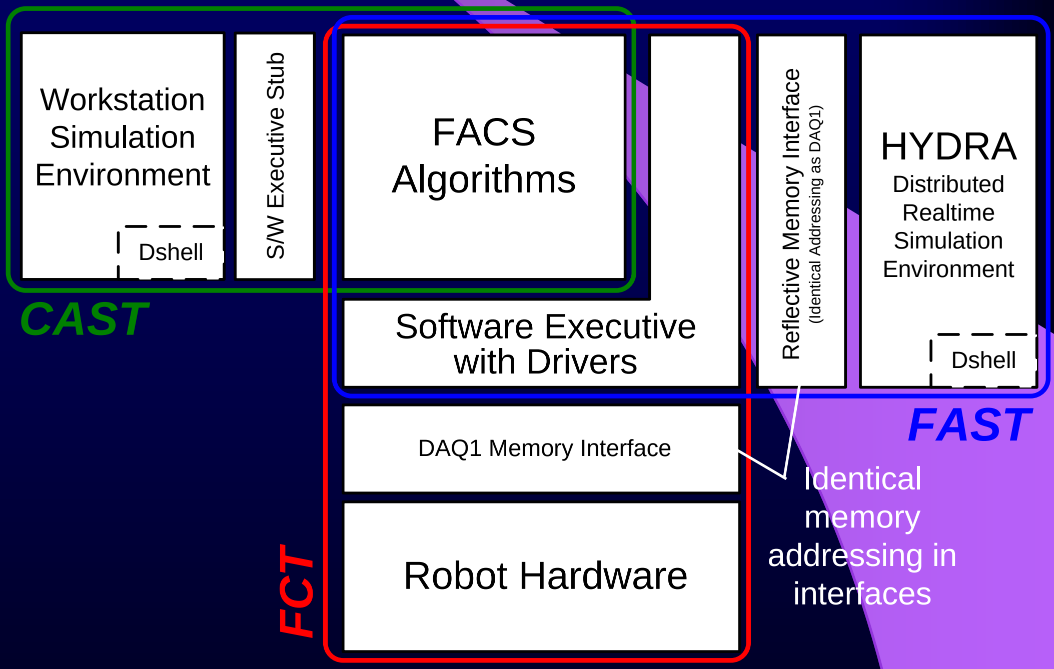
Formation Algorithms and Simulation Testbed (FAST)

- **FAST is a realtime, distributed formation design and simulation environment**
  - Flight-like system components
    - Flight-like CPUs (PowerPC w/ VxWorks)
    - Ground-based operation with high level of autonomy
  - Open architecture for general formations
    - Scalable to large formations (e.g., Stellar Imager)
    - Applicable to different dynamic environments (e.g., LEO)
  - Capable of designing and simulating precision formation flying
    - Collision avoidance
    - Precision formation tracking
    - Autonomous formation reconfigurations
    - Inter-spacecraft communication models (latency, architecture, dropouts)
    - Distributed simulation architecture enforces distributed algorithms

End-to-end performance, functionality, robustness of precision formation flying can be evaluated

FACS Development and Formation Testbeds

- **For formations, traditional ACS is extended to FACS – Formation and Attitude Control System**
- **Three testbeds for verifying and validating FACS**
  - CAST: Control Algorithms Simulation Testbed
    - C-based, non-realtime
    - First end-to-end test in C of FACS
  - FAST: Formation Algorithms and Simulation Testbed
    - C-based, distributed, real-time simulation environment
    - Similar to flight software testbed
    - Flight-like avionics interfaces
    - Real-time inter-spacecraft comm protocols and latencies
    - Software executive for drivers, telemetry, CD&H
  - FCT: Formation Control Testbed
    - 6 DOF robotic testbed with flight-like avionics for validating FAST simulation



FACS is inter-changeable between all three testbeds

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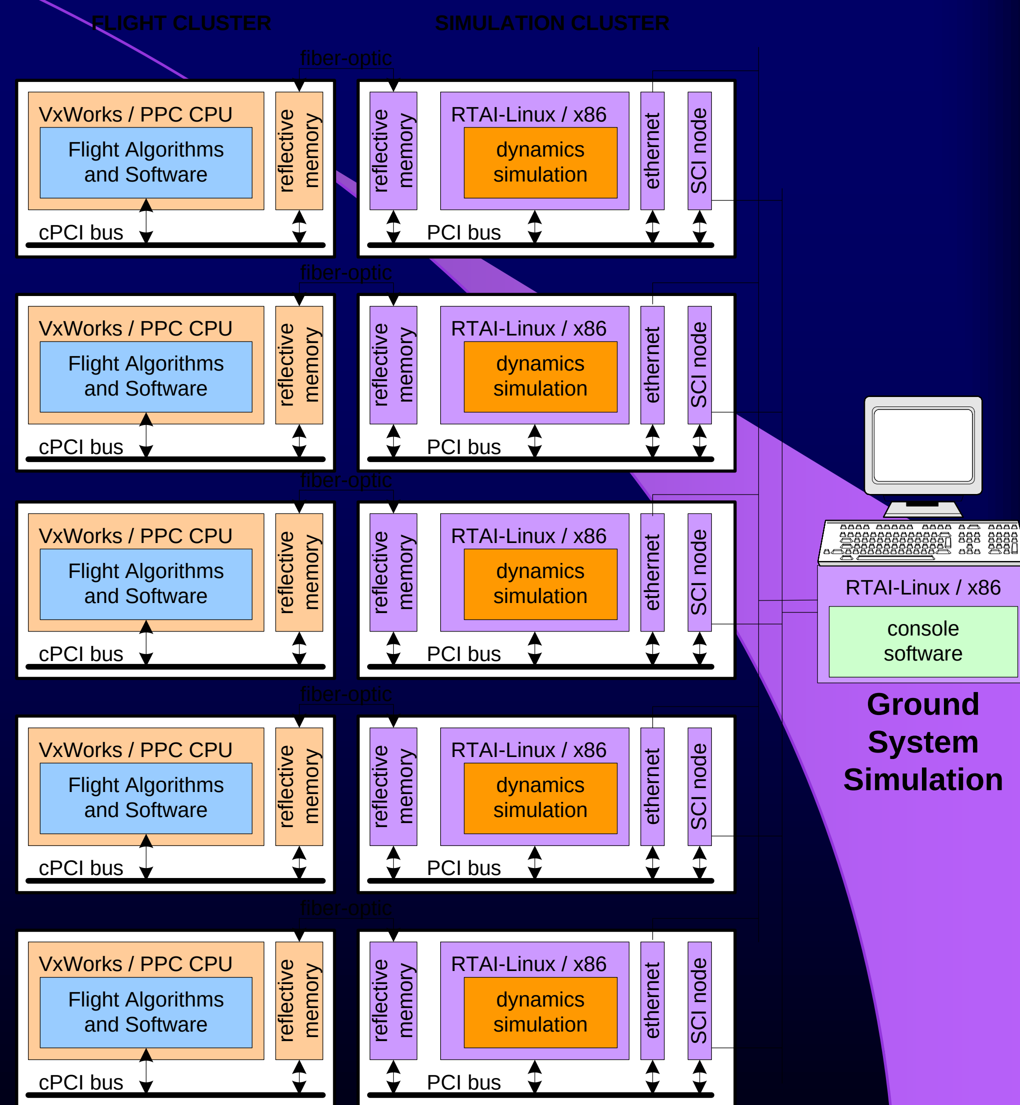
FAST Hardware Architecture



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FCT Robot Configuration

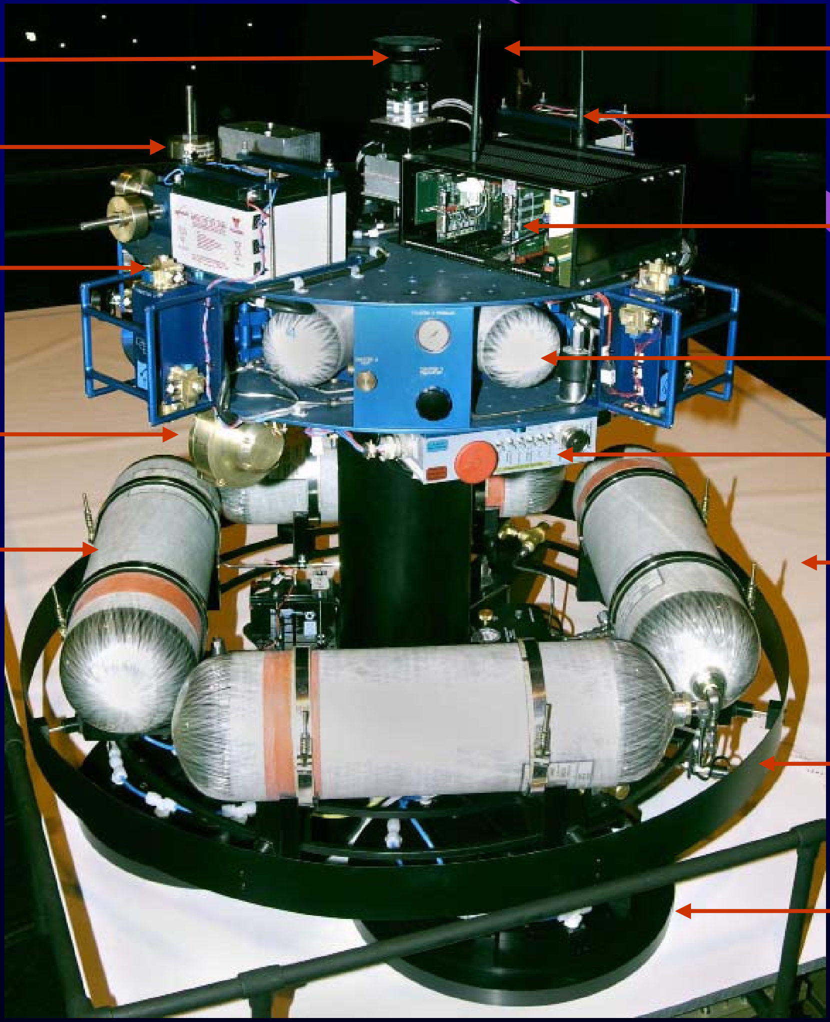
Star Tracker Camera
(PSD Sensor)

Attitude Platform
CG balancing mass
Three per Robot

1N Thruster
16 per Robot arranged in
four orthogonal clusters

Reaction Wheel
Three per Robot

3000 psi Floatation tanks
4 per Robot



High Bandwidth Wireless comm.
(wireless ethernet)

Low-gain wireless comm.
(900 Mhz)

Flight Computer
CompactPCI Bus PowerPC750
VxWorks OS

3000 psi Propellant Tank
8 per Robot

Power & Data Distribution
Electronics

Flat Floor Panels
(4ft x 12ft each)

Protective Bumper
With shock absorbers

Linear Airbearing Pad
(three per robot)

Formation Control Testbed (FCT)

FCT has 6 degrees-of-freedom dynamics with realistic flight-like avionics and components, control architectures, interfaces, operations capable to demonstrate TPF-like formation flying maneuvers

Conclusions

- **Deep Space and Earth Science missions can benefit from formation flying**
  - Large distributed aperture observatories
  - Distributed SAR
- **Significant advances have been made in PFF technologies**
  - Formation guidance, control, and estimation architectures and algorithms
  - Formation sensors, actuators, and communication systems